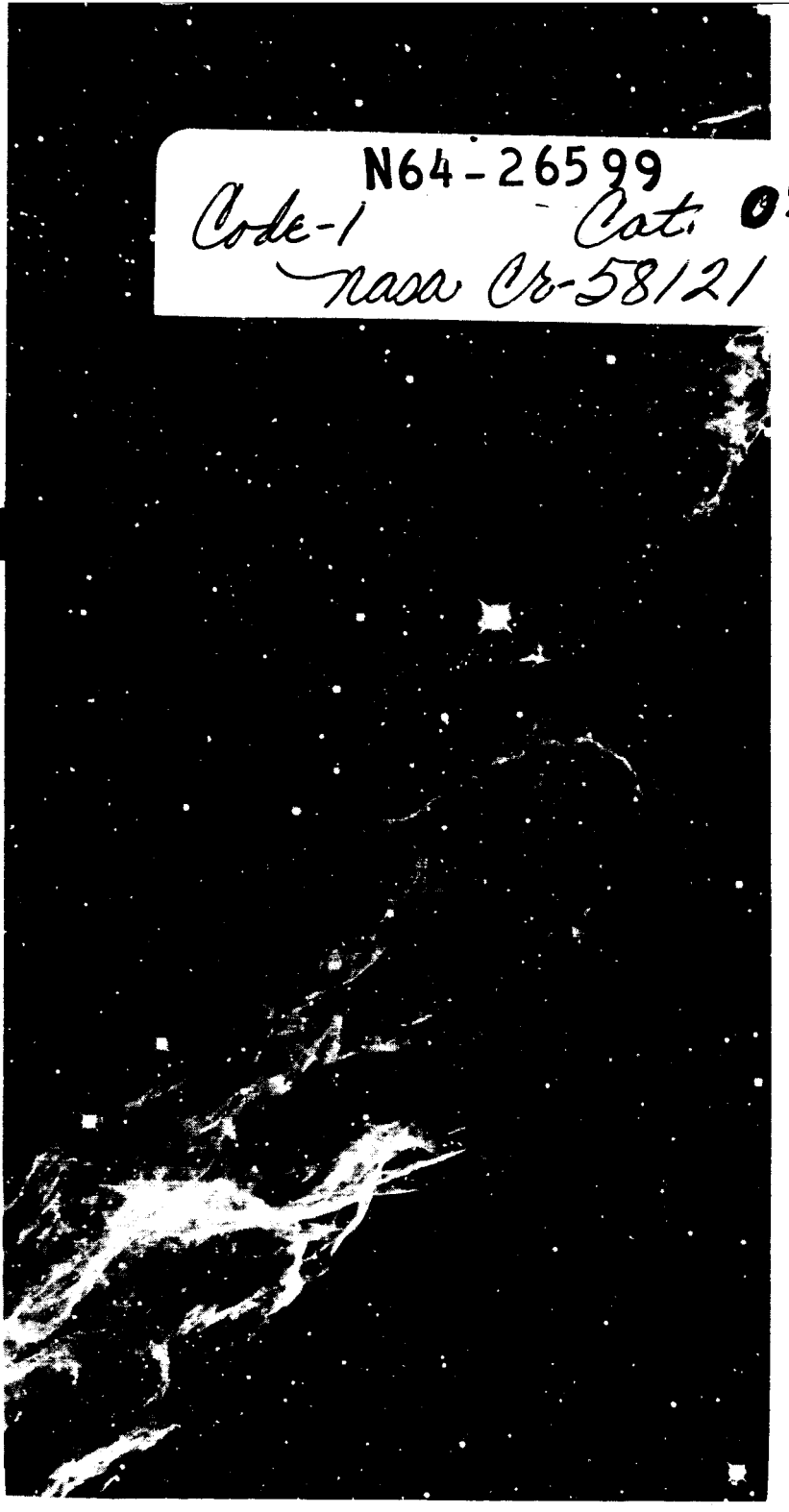
48 p.

ASC

ASTRO
SCIENCES
CENTER

N64-26599
Code-1 Cat. 05
nasa Cr-58121



OTS PRICE
XEROX $ 4.60 ph
MICROFILM $

Digest Report No. P-6

SCIENTIFIC OBJECTIVES FOR MERCURY MISSIONS

REPORTS CONTROL No.

[redacted]

Report No. P-6

SCIENTIFIC OBJECTIVES FOR MERCURY MISSIONS

by

T. C. Owen

Astro Sciences Center

of

IIT RESEARCH INSTITUTE
Chicago, Illinois

for

Lunar and Planetary Programs
National Aeronautics and Space Administration
Washington, D. C.

Contract No. NASr-65(06)

APPROVED:

L. Reiffel, Director

April 30, 1964

ABSTRACT

SCIENTIFIC OBJECTIVES FOR MERCURY MISSIONS

Mercury's orbital elements are well established, the high eccentricity and inclination making it unique among the inner planets. The planet also has an anomalously high density and synchronous rotation. The high density is probably the result of a high proportion of metals in the planet's interior. The synchronous rotation contributes to the extremes in temperature presented by the dark and illuminated hemispheres. While the temperature of the dark side has not been measured, estimates range from 25 to 250 °K. The illuminated surface has a temperature which has been measured as 613 °K at 10 μ and 1100° $\pm$ 300 °K at 3.5 cm. The surface of Mercury resembles that of the moon in its visual appearance, its polarimetric and photometric properties, and its radar reflectivity. The reason for this resemblance seems to be the similar meteoritic bombardment to which both bodies are subject. There is some evidence for a tenuous atmosphere but its composition is still in doubt. Argon has been suggested as a likely candidate since it is cosmically abundant and produced by the natural radioactive decay of potassium. It is heavy enough to be retained by the planet's relatively weak gravitational field. If present, even a thin atmosphere

could have considerable effect as it can transport heat from the illuminated to the dark hemisphere and shield the planet slightly from meteoritic bombardment. No magnetic field or radiation belt has been detected, but it is unlikely that their presence could be deduced from Earth-bound observations, limited as they are by the planet's angular proximity to the Sun. The dark side of Mercury may present an opportunity to examine material which has been accumulating since the origin of the solar system. Organic molecules contained in this material may be of considerable importance to studies of the origin of terrestrial life.

An evaluation of current knowledge about Mercury leads one to conclude that many additional data are needed to answer some of the simplest and most basic questions one might ask. In particular, better measurements of the diameter and mass are required to establish more precise values for the density, surface gravity, and escape velocity. Because of the high density, studies which could determine the state and composition of the interior directly are highly desirable. More accurate measurements of temperature in the microwave region should resolve the present discrepancy between microwave and infrared temperatures and may provide information about the surface and the dark side temperature as well. The kinds of observations which have been made of the illuminated surface should be extended to a large range of wavelengths to provide additional data for a more sensitive test of the similarity between Mercury and the moon. Additional proof of the existence of an atmosphere is needed and if positive results are obtained, an effort should be made to determine its composition directly. Radiation belts and a magnetic field will probably require a spacecraft for their detection and would be

extremely interesting if present. The same requirement and an even greater interest apply to a search on the dark side of the planet for possible pre-biotic organic compounds.

All of these investigations have an importance beyond the additions they would bring to our present knowledge about Mercury. An analysis of Mercury's surface and interior may prove to be of great value for assessing the processes which occurred in the vicinity of the Sun during the formation of the solar system. Data on such things as chemical composition of the crust, state and structure of the interior, and presence or absence of a magnetic field will broaden our present understanding of planetary physics.

In terms of total scientific interest (independent of any practical evaluation of accessibility) we rate Mercury below Jupiter, Mars, Venus, Comets and the Asteroids. Useful data on the surface relief, temperature variations, atmosphere and existence of a magnetic field can be obtained from a Mercury fly-by. The information most pertinent to major scientific issues will probably require some combination of orbiter and lander flights.

TABLE OF CONTENTS

		Page No.
ABSTRACT		iii
1.	INTRODUCTION	1
2.	ORBITAL AND PHYSICAL ELEMENTS	2
3.	TEMPERATURE	8
	3.1 The Illuminated Hemisphere	9
	3.2 The Dark Hemisphere	10
4.	THE SURFACE	12
	4.1 Visual and Photographic Observations	12
	4.2 Photometry	13
	4.3 Polarimetry	14
	4.4 Radar Observations	14
	4.5 Interpretations	15
5.	THE ATMOSPHERE	17
	5.1 Observations	17
	5.2 Theoretical Considerations	18
6.	RADIATION BELTS AND MAGNETIC FIELD	20
7.	BIOLOGY	22

TABLE OF CONTENTS (Cont'd)

		Page No.
8.	CONCLUSIONS	24
	8.1 Orbital and Physical Elements	24
	8.2 Temperature	25
	8.3 The Surface	26
	8.4 The Atmosphere	27
	8.5 Radiation Belts and Magnetic Field	27
	8.6 Biology	27
	8.7 Cosmology	28
	8.8 Evaluation of Mercury Exploration	30
APPENDIX - Notes to Table 1		36
REFERENCES		38

SCIENTIFIC OBJECTIVES FOR MERCURY MISSIONS

1. INTRODUCTION

This report is the sixth in a series of studies being undertaken by ASC/IITRI on the scientific objectives of deep space investigations. Previous studies have been made for Jupiter, the satellites of Jupiter, Comets, the Asteroids, and Interplanetary Space (Roberts 1963, 1964).

Mercury is the smallest known major planet in the solar system. It is also the closest planet to the Sun, a fact which has made it a very difficult object to study. The maximum angular separation of Mercury from the Sun is only 28° (as seen from the Earth) so the astronomer has the choice of observing the planet when it is low in the twilight sky* and thus seen through the most dense and turbulent part of the Earth's atmosphere, or else when it is high in the daytime sky under better seeing conditions but with very low contrast between the planet's disk and the bright sky background. Thus it is not surprising that relatively little is known with certainty about Mercury. In the last few years there has been a renewed interest in Mercury, however, both from the theoretical and observational viewpoints with the result that some of the old uncertainties have been

* Astronomical twilight is defined to end when the Sun is 18° below the horizon. Thus for Mercury to be seen against a dark sky, it can only be 10° above the horizon (at maximum separation from Sun).

removed and a more consistent picture of the planet has developed. This report attempts to summarize what is known and what can be deduced about Mercury's orbital and physical elements, its temperature, surface characteristics, atmosphere, radiation belts and magnetic field, and biological importance. The uncertainties and gaps in our knowledge are indicated and form the basis of the scientific objectives for missions to Mercury. The final section summarizes the conclusions and includes a brief discussion of Mercury's importance in the study of the origin and evolution of the solar system.

2. ORBITAL AND PHYSICAL ELEMENTS

The orbital and physical elements of the planet are summarized in Table 1. The more uncertain measurements are discussed in an appendix at the end of the report.

A comparison of these data with those characterizing the other planets quickly indicates some of Mercury's unique characteristics (see Table 2). Aside from Pluto (which is considered to be an escaped satellite of Neptune rather than a true planet (Kuiper 1957, Rabe 1957)) the orbit of Mercury has the highest eccentricity and greatest inclination to the ecliptic of all the major planets. It is the only major planet whose periods of rotation and revolution coincide. This condition is probably a result of Mercury's proximity to the Sun whose tidal forces would dominate the planet's angular momentum. Thus the rate of rotation of the planet would gradually be diminished as a result of the braking effect of the solar gravitational field. Since the tidal force exerted by a body's gravitational field falls off as $1/r^3$, where r is the distance from the body, Mercury's relatively small distance from the Sun will contribute to the magnitude of the effect. However, MacDonald (1963) has pointed out that even though

Table 1

ORBITAL AND PHYSICAL ELEMENTS OF MERCURY

Orbital Elements[1]

Semi-major axis	0.387,099 AU
Sidereal period	87.9686 days
Synodic period	115.88 days
Mean orbital velocity	47.90 km/sec
Eccentricity	0.205615
Inclination to ecliptic	7° 00' 10.''6

Physical Elements[1]

Radius	2420 km[3]
Ellipticity	0.0
Mass	3.21×10^{26} gm[2]
Density	5.45 gm/cm^3 [3]
Surface gravity	360 cm/sec^2
Escape velocity	4.2 km/sec
Rotation period	88 days
Inclination of equator to orbit	7°[4]
Libration in longitude	23.°7

1) Allen (1963), except as shown
2) Brouwer and Clemence (1961)
3) Dollfus (1963)
4) Dollfus (1962)

Table 2

PLANETARY ORBITS

Planet		Semi-major axis of orbit		Sidereal period		Synodic period	Mean orbital vel.	Eccentricity	Inclination to ecliptic	Mean longitude of ascending node	perihelion	Planet at 1950 Jan 0.
								e	i	Ω	ω	L
		AU	10^6 km	Trop. yrs	days	days	km/s		° ′	° ′	° ′	° ′ ″
Mercury	☿	0.387 099	57.91	0.240 85	87.969	115.88	47.90	0.206	7 00	47 09	75 54	33 10 06
Venus	♀	0.723 332	108.21	0.615 21	224.700	583.92	35.05	0.007	3 24	75 47	130 10	81 34 14
Earth	⊕	1.000 000	149.60	1.000 04	365.257		29.80	0.017			101 13	99 35 14
Mars	♂	1.523 69	227.94	1.880 89	686.980	779.94	24.14	0.093	1 51	48 47	334 13	144 20 07
Jupiter	♃	5.202 8	778.3	11.862 23	4 332.587	398.88	13.06	0.048	1 19	99 26	12 43	316 09 33
Saturn	♄	9.540	1 427	29.457 72	10 759.20	378.09	9.65	0.056	2 30	112 47	91 05	158 18 13
Uranus	♅	19.18	2 869	84.013	30 685	369.66	6.80	0.047	0 46	73 29	169 03	93 12 31
Neptune	♆	30.07	4 498	164.79	60 188	367.49	5.43	0.009	1 47	130 41	43 52	194 37 0
Pluto	♇	39.44	5 900	248.4	90 700	366.74	4.74	0.249	17 10	109 09	224	165 36 0

Table 2 (Cont'd)

PHYSICAL ELEMENTS

Planet		Semi-diameter (equatorial) at 1 AU	Semi-diameter (equatorial) at mean C or O†	Radius (equatorial) R_e		Ellipticity $\frac{R_e - R_p}{R_e}$	Volume	Mass (excluding satellites) M	Density ρ	Surface gravity attractive	Surface gravity equator centrifugal	Escape velocity	Rotation period (equatorial)	Inclination of equator to orbit	Moment of inertia (C)
		"	"	km	⊕ = 1		⊕ = 1	⊕ = 1	g cm^{-3}	cm s^{-2}		km/s		° ′	Ma ⊕
Mercury	☿	3.34	5.45	2 420	0.38	0.0	0.055	0.054	5.4	360	- 0.0	4.2	88^{d}	??	
Venus	♀	8.43	30.5	6 100	0.96	0.0	0.88	0.815	5.1	870	- 0.0	10.3		23?	
Earth	⊕	8.80		6 378	1.00	0.003 4	1.000	1.000	5.52	982	- 3.39	11.2	23^{h} 56^{m}	23 27	0.333 5
Mars	♂	4.68	8.94	3 380	0.53	0.005 2	0.150	0.108	3.97	376	- 1.71	5.0	24^{h} 37^{m}	23 59	0.339
Jupiter	♃	98.47	23.43	71 350	11.19	0.062	1 318	317.8	1.334	2 600	- 225	61	9^{h} 50^{m}**	3 05	0.25
Saturn	♄	83.33	9.76	60 400	9.47	0.096	769	95.2	0.684	1 120	- 176	37	10^{h} 14^{m}***	26 44	0.22
Uranus	♅	32.8	1.80	23 800	3.73	0.06	50	14.5	1.60	940	- 62	22	10^{h} 49^{m}	97 55	0.23
Neptune	♆	30.7	1.06	22 200	3.49	0.02	42	17.2	2.25	1 500	- 28	25	15^{h}	28 48	0.29
Pluto	♇	4.1	0.11	3 000	0.47		0.1	0.8?	*				6^{d}.39		

$M_{\oplus}$ = 5.977 x 10^{27} gm

$V_{\oplus}$ = 1.083 x 10^{27} cm^3

* Density of Pluto uncertain because of apparent discrepancy between radius and mass

** 9^{h} 55^{m} for latitude > 12°

*** 10^{h} 38^{m} for temperate zones

† C = inferior conjunction (Mercury and Venus only)

O = opposition

the solar tide acting on Mercury is about 50 times as effective as the combined lunar and solar tides acting on the Earth, the time required to reduce Mercury's rate of rotation to the present value is long compared with the age of the solar system. He reaches this conclusion by assuming that the planet had an initial angular momentum density proportional to its mass (a relation very closely adhered to by all the other planets except Venus) and that its anelasticity* is equal to that of the Earth. Maintaining the first of these assumptions, he suggests two ways out of this dilemma, namely that Mercury was initially molten and was slowed down by the Sun at this stage or that its present thermal state is such as to allow a much greater dissipation of energy than the Earth. Kuiper (1951) interprets the synchronous rotation of Mercury in terms of his theory of the origin of the solar system. In this view, the original condition of the protoplanets (the large condensations in the primordial solar nebula which became the planets) was synchronous rotation. As the protoplanets condensed, their rotation rates increased in order to conserve angular momentum. In the case of Mercury, this increase in rotation rate was prevented by the solar tidal forces, acting with high efficiency on an object whose loose structure readily permitted the internal dissipation of energy. Thus the planet would never have had a shorter period of rotation than it now exhibits.

As a result of this synchronism, one hemisphere of the planet is constantly facing the Sun, the other is never illuminated. This situation is somewhat moderated by the high eccentricity of the orbit. Although the

---

* If a body is perfectly elastic, there is no mechanism available for the dissipation of its rotational energy. Hence the degree of anelasticity (departure from elasticity) will determine the length of time required for a given force to damp out a given rotational energy.

planet's rate of rotation is constant, its speed in the orbit is not. Thus there are times when the rotation lags behind or leads the speed of revolution with the result that slightly more than one hemisphere is illuminated. This phenomenon is known as libration in longitude and the zones which are alternately illuminated and in shadow are called libration zones. In addition, the fact that Mercury is inclined with respect to its orbit by 7° means that regions 7° beyond the north and south poles will be illuminated alternately as the planet moves around its orbit. The combined effects of longitudinal and latitudinal libration only leave approximately 33% of the planet's surface area completely unilluminated. There may also be small, as yet undetected oscillations about the axis of rotation similar to those exhibited by the Earth's moon (which also rotates synchronously).

One of the great puzzles presented by Mercury is its high density. The planet's mass is too small for its interior to have undergone the compression which is responsible for the high mean density of the Earth. The crust and interior of the Earth are estimated to have mean densities of 2.64 and 17.3, respectively, while the corresponding value for the planet as a whole is 5.52. Urey (1957) has attempted to remove the effects of compression by computing a mean density at zero pressure which he gives as 4.4. The same technique applied to Mercury produces a value only slightly less than the measured quantity, viz., 5.4 instead of 5.45. Since compression will not account for the high density, Urey suggests that it is due to a difference in composition. While the Earth is generally assumed to be composed primarily of silicates with a metallic core, Urey postulates that Mercury has a high abundance of metals throughout its interior and a

silicaceous crust. Accepting for the moment the idea that Mercury has a disproportionately high content of metals as compared with the Earth, the reasons for this concentration must be explained. Urey (1951) suggests that in the formation of the planets the silicate phase rather than the metallic phase would be lost preferrentially since it would float on the surface of melts of silicate and metallic iron and thus would be more readily acted upon by evaporation and mechanical processes. Kuiper (1952) supports this hypothesis and adds the suggestion that the silicates formed an oxide smoke which was blown away by solar radiation pressure or solar corpuscular radiation. According to this model, there should be a trend (among the inner planets) toward decreasing density with increasing distance from the Sun, independent of mass. This indeed seems to be the case, the uncompressed mean densities of Mercury, the Earth and Mars being 5.4, 4.4, and 4.02, respectively (Urey 1957). The corresponding value for Venus is less certain but Urey gives a value of 4.4 which seems to be consistent within the probable error associated with the calculations. It seems safe to assume as a working model that the planet consists of an interior having a high metallic content which is covered by a layer of silicate material.

3. TEMPERATURE

In spite of the moderation introduced by the librations, the basic configuration of synchronous rotation near the Sun with little if any protecting atmosphere has given the surface of Mercury an extreme range in temperature.

3.1 The Illuminated Hemisphere

The theoretical temperature of an insulated black surface at the distance of Mercury from the Sun is 633 °K (Allen 1963). This is the maximum temperature that a solid body at this distance can attain. Pettit (1961) has derived a mean subsolar temperature of 613 °K from his thermocouple-radiometer measurements which indicates that Mercury behaves very nearly as a black body. Pettit computes the extreme temperatures as 688° at perihelion and 558° at aphelion. These results are commensurate with a low rate of heat conduction through the planet, a low visual albedo, and the absence of an appreciable atmosphere (which would transport heat to the dark side of the planet by convection). The low visual albedo is an observed fact; the role of an atmosphere and the material of the surface and interior as heat transport mechanisms is discussed below.

Howard et al., (1962) have derived a temperature of 1100° $\pm$ 300° K from microwave measurements made at 3.5 cm (Pettit's radiometer measurements were made through the infrared optical window in the Earth's atmosphere between 9 μ and 14 μ). As this figure is in excess of the theoretical black body temperature it must be regarded with some caution. The authors point out that the radiation flux density from Mercury is near the limit of their instrument's sensitivity and that the planet's angular proximity to the Sun is a great problem since the latter is an intense source of microwaves. The combined effect of these two factors leads the authors to conclude that the discrepancy between the infrared and microwave temperatures is comparable with the uncertainty in the microwave observations. One further problem has to be considered, however, namely the level below the surface at which the microwave radiation originates.

If one assumes that the surface of the planet is covered by a lunar type dust layer (some reasons in support of this assumption will be given in section 4) then using the models formulated for the lunar case one finds that the depth of escape of 3 cm waves is 84 cm. Now if there is a steep subsurface thermal gradient set up by (say) radioactive heating from the interior, then radiation from beneath the surface on the dark side will contribute to the observed microwave flux. On the assumption of a lunar type dust cover and the dark side surface temperature derived by Walker (1961 - see below), Howard et al., find that they can reduce the subsolar temperature to 1030°K by subtracting the contribution of the dark side. Their analysis does not include the effects of a lunar type model on the temperature of the illuminated side, however, and thus is incomplete. Clearly additional observations are needed.

3.2 The Dark Hemisphere

The temperature of the dark side cannot be measured directly from the Earth but certain constraints on it can be deduced. From a consideration of the effectiveness of conduction through the planet from the hot side, the energy dissipated by meteoritic bombardment, and the contribution of radioactive heating, Walker (1961) has derived a dark side temperature of 28°K. Sagan and Kellogg (1963) have criticized this result because the thermal conductivities used may not be high enough in view of the concentration of metals expected in the interior to explain the high density. This criticism seems unjustified, however, since Walker in fact estimated the effects of a high thermal conductivity and found that the dark side temperature would be raised to a maximum of 32°K if the conductivity were 40 cal deg^{-1} cm^{-1} min^{-1} throughout the planet. It seems more likely

that Walker's temperature is a bit too high since he has assumed that Mercury has the average composition of the chondrites* and thus a similar amount of radioactivity. MacDonald (1963) has pointed out that the high mean density of the planet makes a chondritic composition unlikely. If the composition is largely metallic, then a lower concentration of radioactive elements is indicated. Nevertheless, MacDonald feels that with Mercury's low mass, the absence of extensive compression referred to in section 2 will mean that the melting point of the interior material is not substantially raised and thus a lower concentration of radioactive elements, 1/3 to 2/3 that of the Earth, would still be sufficient to make Mercury largely molten at present.

Field (1962) has advanced another argument in favor of a somewhat higher temperature. Using the mass and surface pressure of the atmosphere derived by Dollfus (1961) (see below) and following Kuiper's (1952) suggestion that Mercury could retain radiogenic argon, Field points out that an argon atmosphere could only exist at this pressure if the dark side temperature were higher than 56 °K. At lower temperatures the argon would freeze out. Field suggests convective transport by the atmosphere as the mechanism responsible for this increase over the temperature predicted by Walker. He adds that the microwave observations of Howard et al., (1962) (section 3. 1) may be indicative of a dark side temperature as high as 250 °K, a hypothesis which could be tested by additional microwave studies.

---

* The chondrites are the largest class of stony meteorites. They get their name from the presence of small spherical grains called chondrules which are imbedded in the meteorites.

4. THE SURFACE

The surface of Mercury has been the subject of intensive investigations using several different observational techniques. The results obtained by means of these techniques are summarized below. In all cases comparisons are made with the Earth's moon (and occasionally with other objects) in order to illustrate the significance of the observations. The implications of the similarities which appear to exist between the surfaces of Mercury and the moon will be discussed in the concluding section of the report.

4.1 Visual and Photographic Observations

The observational problems referred to in the introduction have made the mapping of Mercury's surface a difficult task. Dollfus (1962) has summarized the best work of past observers as well as recent photographic and visual observations made by himself and his colleagues at the Pic du Midi Observatory. With the inclination to the orbit plane and the extent of longitudinal libration given in Table 1, Dollfus was able to construct a planisphere (a polar projection of the globe onto a plane) of the illuminated hemisphere which was consistent with the available observations. All of the visual observers seem to agree that there are great similarities between the general appearance of Mercury when viewed with high magnification and that of the moon as seen with the naked eye. Both objects show dark areas of low contrast superimposed on a light background. Dollfus (1962) has examined the terminator of the planet under ideal conditions and concludes that there is no evidence for relief on the surface. This only means that any relief which may be present must be less than twice as great as that found on the moon.

4.2 Photometry

The similarity in appearance between Mercury and the moon is supported by photometric studies of their surfaces. Their albedos (at λ = 5500 A)* have been measured as 0.056 and 0.067, respectively. For comparison, the albedo of the asteroid Pallas is 0.053; of Mars 0.16; of Venus, 0.76 (Allen 1963, Harris 1961). Pallas is the second largest of the asteroids with a diameter of 306 miles. It is too small to retain an atmosphere, hence the albedo refers to its rocky surface. Mars has a tenuous atmosphere but a pattern of light and dark areas reminiscent of the moon and Mercury. Venus has an extensive, cloud filled atmosphere; the high albedo is a consequence of the high reflectivity of the clouds. The corrected color index** of the moon is (B-V)' = + 0.29, while that of Mercury is + 0.30. Pallas has a color index of - 0.4 (it is "bluer" than the Sun) while for Mars and Venus the values are + 0.71 and + 0.19, respectively (Allen 1963, Harris 1961). The variation of light intensity with phase angle (angle between Sun and Earth seen from the object being studied) is also similar (Dollfus 1962). None of these three measurements taken by itself defines the characteristics of a planet's surface uniquely since in each case there are several types of surface structure and/or composition which will produce the observed result. However, all three measurements taken

* The albedo given here is the Bond albedo defined as the ratio of the total flux reflected in all directions to the total incident flux. These albedos are determined for a wavelength near the maximum of the solar black body curve.

** If one measures the magnitude of a planet or satellite in well defined (e.g., by interference filters) wavelength intervals and subtracts one of these magnitudes from another, the resulting difference implies a certain reflectivity gradient with wavelength and is referred to as a color index. If one then subtracts the color index of the Sun, one obtains a corrected color index which will be a measure of the color of the planet's (or satellite's) surface. The wavelength intervals commonly used for this purpose are centered at 0.554μ (V) and 0.448μ (B).

together carry more weight. The fact that they appear to exhibit a more consistent similarity with comparable data obtained for the moon than for other bodies may therefore indicate a real similarity between the surfaces of the moon and Mercury.

4.3 Polarimetry

The early polarimetric work of Lyot has been confirmed and extended by Dollfus (1961, 1962). The observations indicate a general similarity between the polarization vs. phase curve for Mercury and the moon. In addition, Dollfus has found that as the phase angle increases, the degree of polarization increases more rapidly in green light than in red for the planet as a whole, and the polarization of the dark areas becomes stronger than that of the light regions. Both of these phenomena are found to occur on the moon (Gehrels 1963).

4.4 Radar Observations

As of this writing, radar contact has been made with the moon, Venus, Mars, and Mercury. Radar observations show Mercury to be approximately twice as rough as Venus at 12.5 cm (Carpenter and Goldstein 1963), but it is not clear from the published report how this roughness was determined. Carpenter (1964) has reported that the root mean square surface inclination on Venus is roughly half that of the moon at this wavelength. If the Mercury results were interpreted with the same kind of analysis, they imply that the surface of Mercury has about the same roughness as that of the moon at 12.5 cm, strengthening the similarity indicated by

the optical observations. It is more likely that the conclusion about the roughness of the surface does not take into consideration the possibility of a different dielectric constant and thus the conclusion about surface roughness probably rests on the assumption that the dielectric constants are also similar. In view of the evidence given above, this may not be a bad assumption.

4.5 Interpretations

Dollfus (1961) has shown that laboratory studies indicate that the lunar polarization vs. phase angle curve is well matched by opaque powder. The origin of this powder on the moon is ascribed to meteoritic bombardment or exfoliation (splitting off of surface layers of rocks) due to the extreme heating and cooling cycle of the moon. Dollfus (1962) suggests that the latter alternative can be eliminated on the basis of the Mercury polarization results since the visible face of the planet is subject to constant illumination. As was pointed out in section 3.1, however, this constant illumination does not occur at a constant temperature. The temperature difference caused by the eccentricity of Mercury's orbit is about 130°, that suffered by the lunar surface is about 300°. In addition, the mean temperature about which the variation in temperature occurs may also be important since it might be a critical temperature from the standpoint of the properties of the surface material. Thus Dollfus' conclusion that the lunar surface properties (and hence those of Mercury's surface as well) must be ascribed to the action of meteoritic bombardment exclusively seems too strong. Nevertheless, we know the moon is being bombarded constantly by small meteorites and there is considerable evidence that the craters and ringed plains on its surface were formed by impacts of large bodies (Baldwin 1963,

Shoemaker 1962). Hence it seems likely that the microstructure of the surface is determined at least in part by the effects of bombardment. We may now ask whether it is reasonable to expect bombardment to play a similar role in the formation of the microstructure of the surface of Mercury.

Hodge (1963) has considered this problem in some detail. He estimates that the space density of interplanetary material at Mercury's distance from the Sun is roughly three times that at 1 AU. Considering the orientation of the particle orbits, the impact velocities and the amount of displaced material he concludes that the planet's surface has been severely eroded by interplanetary matter, probably to the same extent as the weather-caused modifications of the Earth's surface. He adds that meteoritic erosion has the almost irreversible effect of making material increasingly smaller in size and thus he expects the surface of Mercury to be largely dust covered. This conclusion seems consistent with the observations reported above. Furthermore, the only plausible structure which has been found to reproduce the lunar photometric phase curve is the so-called "fairy castle" configuration which fine dust particles assume when sifted onto a flat surface (Hapke 1963). Thus both the polarization and photometric measurements appear to require a dust covered surface and a suitable mechanism for forming such a surface has been suggested. As stated above, however, this may not be the only dust-producing mechanism and even if it is, the erosion it produces may be offset to a certain extent by new material brought to the planet's surface by igneous activity while the erosion rate will be diminished by the presence of a tenuous atmosphere. These factors will reduce rather than abolish the effect, however, so the basic picture may still be correct.

5. THE ATMOSPHERE

5.1 Observations

Kuiper (1964) has listed seven ways in which a planetary atmosphere can be recognized by Earth-based observations. These are a) variable clouds; b) polar caps; c) spectroscopic evidence; d) variable polarization for a given phase angle; e) shape of the photometric phase function; f) presence of limb darkening; g) ultraviolet excess (not conclusive evidence). Of these criteria, only (d) is definitely satisfied in the case of Mercury. Antoniadi (1934) has reported observations of extensive cloud cover and haze but these have not been confirmed by the careful studies of Lyot and Dollfus (1961). Observations of the infrared spectrum have not revealed any absorptions attributable to an atmosphere (Kuiper 1952, 1963) but Kozyrev (1963) has reported emission lines in the visible spectrum which he believes have an atmospheric origin (see below). A recent press release in Pravda reports that Moroz (1964) has discovered carbon dioxide in the infrared spectrum of Mercury at 1.575 and 1.606μ. Since Kuiper's spectra referred to above were obtained at higher resolution and show nothing, this report must be viewed with some skepticism. The polarization evidence consists of the observation by Dollfus (1961) that at large phase angles, the degree of polarization* increases from the center of the

* Define the plane of vision by the directions of illumination and observation. An observed beam of light may be considered as made up of two component vibrations, the intensity I_1 being normal to the plane of vision and the intensity I_2 being in the plane. The degree of polarization is defined as

$$P = \frac{(I_1 - I_2)}{(I_1 + I_2)}$$ (Dollfus 1961).

crescent to the limb and is greater at shorter wavelengths. These two characteristics are exactly what one would expect to find if the planet were surrounded by a thin, gaseous envelope. Assuming that the gas is similar to air, Dollfus derives an atmospheric pressure of about 1 mb, i.e., 10^{-3} atm.

5.2 Theoretical Considerations

In order for a planet to retain an atmosphere, the root mean square velocity of the molecules must be less than the velocity of escape. Jeans has shown that an atmosphere will be stable for periods of time greater than a billion years if $V_{rms} < 0.2\ V_{esc}$, a result which is applicable to isothermal atmospheres if properly interpreted (Kuiper 1952). The root mean square velocity of the molecules is a function of the temperature of the gas T and the molecular weight μ such that

$$V_{rms} = \sqrt{\frac{3\ RT}{\mu}}$$

where R is the universal gas constant ($R = 8.317 \times 10^{7}$ erg deg^{-1} mol^{-1}). Using Pettit's mean subsolar temperature of 613°, this works out to

$$V_{rms} = 3.911\,\mu^{-1/2} \text{ km/sec.}$$

From Table 1 we have

$$V_{esc} = 4.2 \text{ km/sec.}$$

Applying Jeans' criterion, we can find the condition for the molecular weight which will ensure atmospheric stability:

$$3.911\,\mu^{-1/2} < 0.2 \times 4.2 \text{ or}$$

$$\mu > 21.7$$

Now a diatomic gas may be expected to be partially dissociated at any time due to the intense solar ultraviolet radiation incident on the planet. Thus the choice of constituents for a Mercurian atmosphere is essentially limited to monomolecular gases of high atomic weight, i.e., the heavier noble gases. The most cosmically abundant of these is argon with $\mu = 40$. Furthermore, the most common isotope of argon, A^{40}, is produced radiogenically by the decay of radioactive potassium. Since potassium is relatively common in the Earth's crust and in meteorites, it seems reasonable to expect continuous argon production occurring at the surface of Mercury.

Following this logic, Field (1962) has suggested that the atmosphere detected by Dollfus consists primarily of argon. Using the surface pressure and atmospheric mass derived from the polarization measurements, Field has been able to place a constraint on the dark side temperature as mentioned above. He points out that the mass of argon composing the atmosphere of Mercury is 1.0×10^{-8} times the mass of the planet while the same ratio for the Earth is 1.1×10^{-8}. Although he does not attach much weight to this virtual identity, Field suggests that it may imply fundamental similarities between the mass and constitution of the mantle, the effectiveness of degassing and the exospheric* temperatures of the two planets.

Sagan and Kellogg (1963) have pointed out that if the exospheric temperature on Mercury is greater than 2000° K, argon will escape readily

* The exosphere is that layer of a planet's atmosphere at which the mean free path of the constituent molecules exceeds the local scale height, i.e., collisions are negligible. Hence the temperature of this layer is critical in determining the possibility of escape of molecules (Spitzer 1952).

from the planet and thus could not be the major atmospheric constituent unless it was produced at a very high rate. While this statement is correct as it stands, we have at present no way of calculating what a reasonable value for this temperature should be. As possible alternatives they suggest krypton, xenon, and radon, but the most abundant of these (krypton) is cosmically rarer than argon by three orders of magnitude (Allen 1963) and thus is unlikely to be a major atmospheric constituent.

Another alternative to the argon atmosphere has recently been proposed by N. Kozyrev (1963) who has reported observations of hydrogen lines in emission in the spectrum of Mercury. The observations are only described - with no illustrations of densitometer tracings or spectra - so they are difficult to assess. Kozyrev claims that the escape of hydrogen required by the theoretical arguments given above can be compensated by the expected high influx of solar protons at Mercury's distance from the Sun. He does not describe how these protons are captured and how they combine with electrons, however, so again there is insufficient information for a proper evaluation. Until such information is available, a certain amount of skepticism seems advisable in view of other questionable observations reported by Kozyrev in the past (Sagan and Kellogg 1963, Weinberg and Newkirk 1961).

6. RADIATION BELTS AND MAGNETIC FIELD

There is as yet no indication of either a magnetic field or radiation belts around Mercury. The microwave observations of Howard et al., (1962) referred to in section 3.1 were made at 3.5 cm, a wavelength at which no non-thermal radiation component (from radiation belts) would be expected. Thus in the case of Jupiter which has extensive radiation belts

and possibly a strong magnetic field as well, the black body temperatures derived from 3.5 cm observations are in close agreement with temperatures determined from model atmospheres and rotational temperatures of the atmospheric gases (Gallet 1961, Zabriskie 1962). It is only as longer wavelengths are used that the non-thermal radiation becomes noticeable. Since there is very strong interference from the Sun even at 3.5 cm because of its angular proximity to Mercury, it will probably not be possible to observe Mercury at longer wavelengths (where angular resolution is lower) to look for non-thermal radiation until space probes are available for this purpose.

The question of whether Mercury possesses a magnetic field is of special interest in view of the recent discoveries that Venus and the moon have very small fields, if any (MacDonald 1963). As yet there is no definitive theory for the causes of planetary magnetic fields but it is generally agreed that they are related to a planet's rotation and the presence of a liquid metallic core (MacDonald 1963). Thus the fact that Venus exhibits very slow (retrograde) rotation (Carpenter and Goldstein 1963) may be consistent with a very weak magnetic field. The moon does not rotate as slowly as Venus but its low density implies that it cannot have a large metallic core so the absence of a strong field is again understandable. Mercury rotates very slowly but has a high density and thus represents an intermediate case. As indicated in section 3.2, there are some reasons for expecting that the planet has a liquid core. In addition, one should not exclude the possibility that Mercury has acquired a trapped field so that even if the core is not liquid and despite the slow rotation, a magnetic field might be present. One should remember, however, that these conclusions

are based on theories which can only be tested by additional measurements of the magnetic field strengths of the various planets with a concurrent formulation of models of their interiors.

7. BIOLOGY

From the evidence which has been presented thus far, Mercury would seem to be one of the least interesting objects in the solar system from a biological standpoint. The extremes of temperature, lack of an appreciable atmosphere, and exposure to intense solar radiation contribute to an environment which is extremely hostile to the development of life as we know it. When one considers the problem of the origin of life, however, the "cold-storage" properties of Mercury's unilluminated hemisphere become very significant.

Current theories about the origin of terrestrial life take as their starting point the formation of a suitable pre-biotic environment. This environment must include complex organic substances (Lederberg 1960). It has been amply demonstrated that there are many ways in which such substances can be synthesized without the help of living organisms (Fox 1960), but the important problems of the location and time of such syntheses are not yet well understood. Lederberg and Cowie (1958) have suggested that fairly complex organic structures may be present in the interstellar grains whose light absorbing properties are well known to astronomers (Dufay 1957). In addition, the carbon-rich spectra of comets may imply the presence of fairly complex organic molecules in the frozen cometary nuclei. In both cases, the authors suggest that some of this material may be expected to be accreted by the moon. A much larger quantity of non-organic meteoritic matter would also accumulate on the lunar surface and

might in fact protect the organic material from solar radiation and the temperature extremes of the lunar thermal cycle. In a later paper, Lederberg (1961) points out that the dark side of Mercury would be even better suited as a repository for such substances, presumably because of its low temperature and the fact that it is constantly shielded from the Sun.

It is interesting to note that these ideas are variations on the hypothesis of panspermia advanced by Arrhenius (1908) whereby life was transmitted from planet to planet in the form of spores. In the present instance it is not life itself which is held to be universally present (within the galaxy) but perhaps some of the precursors of life.

Sagan (1961) has advanced the idea that aside from organic particles which may have been deposited on the moon from interstellar or interplanetary space, it is possible that the moon's surface contains indigenous organic material created in its atmosphere in the early stages of the solar system. If one concedes that the planets condensed out of a solar nebula in which the abundances of the elements were roughly the same as the present cosmic abundances, then it is highly likely that the primitive moon was surrounded by an atmosphere consisting primarily of CH_4, NH_3, H_2O with smaller amounts of H_2 (the first gas to escape) and interaction products. In fact, Sagan suggests that an atmosphere of this type could even be secondary in origin as a result of the initial outgassing of the moon. He calculates that the Sun at this stage would have a strong enough ultraviolet flux to synthesize a considerable number of organic molecules of fair complexity in a manner which has been demonstrated in laboratory experiments (Miller 1955).

Again one could extend these arguments to the case of Mercury if sufficient circulation existed in the primitive atmosphere to carry the reaction products to the dark side of the planet. If left on the surface of the illuminated hemisphere, the intense heating would quickly destroy the molecules, even under a fairly thick layer of dust.

There are thus two separate possibilities for the accumulation of a deposit of organic matter in the subsurface layers of the dark side of Mercury. It is perhaps worthwhile to stress that organic matter is by no means synonomous with nor does it even imply the existence of life itself. This does not decrease its importance, however, since its presence is a necessary requirement for the origin of life. Only from an investigation of planetary environments which have not been contaminated by terrestrial life can we gain real insight into the type of biologically favorable conditions which must have existed on the Earth before life began.

8. CONCLUSIONS

In the following paragraphs, the discussion presented in each section of the report is summarized and the additional data required for resolution of the existing uncertainties are indicated. A sub-section to indicate the importance of Mercury with respect to ideas about the solar system as a whole is also included. The report is concluded by an evaluation of the Mercury scientific objectives both on their own merits and as they relate to the general program of exploration of the solar system.

8.1 Orbital and Physical Elements

The orbital elements are well established. For the physical elements comparable certainty doesn't exist. The period of rotation and the amount of longitudinal libration are fairly well known but small .

oscillations by the planet about its axis of rotation may occur, requiring greater accuracy than is presently available for their detection. Of particular importance are better values for the mass and the diameter since the surface gravity, the escape velocity, and the density are determined by these quantities. The present uncertainties are insufficient to account for the unusually high value for the mean density derived from available data. The high density constitutes an interesting anomaly which has been explained by postulating that Mercury has a high metallic content. Clearly studies which could determine the composition and state of the interior of the planet would be very desirable.

8.2 Temperature

8.2.1 The Illuminated Hemisphere

The temperature of the illuminated hemisphere has been determined by two different techniques at two different effective wavelengths (10 μ and 3.5 cm) resulting in two different values (613° K, 1100° K). At present, the accuracy of the infrared method is considerably greater than that of the microwave technique, hence this disagreement may not be real. If it is real, it may imply a higher temperature for the dark side of the planet than has been anticipated. Since the microwave radiation probably originates from a subsurface layer rather than from the surface itself, in principle the technique is capable of yielding information on the subsurface thermal gradient. Additional ground based observations are needed.

8.2.2 The Dark Side

The dark side temperature has not been measured directly, but theoretical models have been constructed to predict it.

Uncertainties in the interior structure and composition of the planet make such models tentative at best but low temperatures (on the order of 30 °K) seem indicated. If a tenuous atmosphere is present to transport heat from the illuminated to the dark side, higher values may be achieved. In this case, a lower limit on the temperature is set by the condensation temperature of the atmosphere at the postulated pressure. Upper limits can be set by accurate ground based microwave observations.

8.3 The Surface

Observations of the surface by any technique are difficult from Earth because of Mercury's angular proximity to the Sun. Visual, photographic, photometric, polarimetric, and radar observations appear to show interesting similarities with like observations of the surface of the Earth's moon. The composition and microstructure of the lunar surface are not yet well understood, but the models which have been suggested to explain the various observations are not in contradiction with present ideas about the manner in which the surface of Mercury has been formed. In particular, it appears that erosion due to meteoritic bombardment may have been sufficient to produce a surface dust layer which could account for the observational data.

All the types of observations listed above could be carried out in greater detail by working at as large a range of wavelengths as possible. Results from such work would permit a more extensive and hence more sensitive comparison with the lunar data to see how close the similarity between the surfaces of the moon and Mercury really is. Since the moon is the subject of increasing scientific interest and will soon be studied *in situ*, such a comparison may be able to tell us a great deal about Mercury

that we could not learn otherwise without going there.

8.4 Atmosphere

The presence of a Mercurian atmosphere has been suggested by visual observations of haze, spectroscopic observations showing hydrogen emission, and polarimetric observations indicating an increase in the strength of the polarization at the limb and in shorter wavelengths. Of these methods, the last seems most reliable. Using the polarization data an argon atmosphere has been postulated which appears to be consistent with present knowledge of cosmic abundances and theoretical values for atmospheric escape rates. Additional observations are needed to verify the presence of the atmosphere and to try to establish its composition.

8.5 Radiation Belts and Magnetic Field

At the present time there are no observations which could be used to derive information about either a magnetic field or radiation belts. It seems unlikely that the required observations could be made from the Earth. Theories for the production of planetary magnetic fields are not in conflict with possible models for Mercury's interior, but as indicated above, the latter are still in a primitive state. On the other hand, so are the theories. Thus observations of Mercury's magnetic field coupled with better information about its interior would make an important contribution to current ideas about planetary physics.

8.6 Biology

Although the Mercurian environment is extremely hostile to life as we know it, the dark side of the planet may have organic material preserved on its surface which would be extremely interesting for studies

of the origin of life. This material could be in the form of accreted interstellar grains or fragments of comet nuclei or may have been produced indigenously in the planet's primeval atmosphere. A study of this accumulated material would thus give an indication of the type and quantity of organic matter which may have been present on the Earth's surface before life began.

8.7 Cosmology

The problem of the origin and evolution of the solar system obviously cannot be solved by studying only one of its members. Nevertheless, such a study can contribute significantly to the larger problem. As was pointed out in section 4, the surface of Mercury appears to resemble that of the moon. Both are small bodies with very tenuous atmospheres, if any. As such, they are subject to meteoritic bombardment which may be expected to form the surfaces in similar ways. While there are good reasons to expect large quantities of small meteorites in Mercury's vicinity, it is not so clear that larger bodies would be present. It has been suggested that the ringed plains and even the dark maria on the moon were formed by impacts of such bodies, some of which may have been remnants of the process which formed the moon and the Earth (Baldwin 1963, Kuiper 1954). The dark areas on Mercury are reminiscent of the lunar maria; this similarity should be explored. The topography of the planet may well provide a record of the sizes of bodies which were present in the early history of the solar system near the Sun.

With all these similarities between Mercury and the moon, the planet's high density stands out in glaring contrast. This anomaly must have occurred at the time Mercury was formed; hence its explanation has a

bearing on the formation process itself. The same may be said about the conditions leading to the presence or absence of a liquid core and a magnetic field. In order to arrive at any fundamental understanding about the forces operative in planetary interiors we need more than our present, single example,the Earth.

The importance of the dark side of Mercury for biology has been stressed in section 7. It should be pointed out that materials other than organic molecules will be stored there and preserved to a greater extent than on the lunar surface. Some of the accreted matter will be ground finely enough to be ejected from the planet by repeated impacts. In any case, the intensive bombardment which is anticipated will probably stir up the surface sufficiently to prevent a chronologically ordered stratification of the deposited material (Sagan and Kellogg 1963). Nevertheless, a record will be there and the development of the necessary procedures for its proper interpretation should not be an unsolvable geological problem.

Aside from impact material, the composition of the crust of Mercury will also be of great interest. Our present data on cosmic abundances are limited to studies of meteorites, the Earth's crust, cosmic rays, the Sun and the stars. We suspect that Mercury's high density indicates a differentiation of primeval material quite different from that undergone by the Earth. It will be of great interest to see whether this difference shows up in the crust as well. In addition, reference should be made to the proposal of Fowler, Greenstein, and Hoyle (1962) that the light elements D, Li, B, and Be were produced by spallation and neutron reactions during an intermediate stage in the early history of the solar system. The high energy particles responsible for these reactions are postulated to have

been accelerated in magnetic flares at the surface of the condensing Sun. If this theory is correct, there should be a gradual decrease in the abundance of these elements with increasing distance from the Sun. In particular, the isotope ratios D^2/H^1, Li^6/Li^7, and B^{10}/B^{11} should change. These ratios could be determined from an analysis of the composition of Mercury's crust.

To sum up, there are at least four ways in which a study of Mercury should contribute directly to the problem of the origin and evolution of the solar system. The topography of its surface may reveal the size distribution of bodies which were present in the early stages of the solar system's formation. Its interior structure should provide insight into the way in which the planet itself was formed and perhaps give an indication of the mechanism responsible for the formation of planetary magnetic fields as well. The dark side of the planet should contain a record of the types of inorganic and organic matter which have been bombarding Mercury (and thus to some extent, the other inner planets) since it formed. Finally, an analysis of the chemical composition of the crust may indicate the type of differentiation suffered by the material which was to make up the planet while in its uncondensed phase and shed some light on the problem of synthesis of the elements in the early history of the solar system.

8.8 Evaluation of Mercury Exploration

In attempting to evaluate the significance of the scientific objectives for Mercury missions there are three points to consider:

a) What is the importance of knowledge gained about Mercury relative to what could be learned on missions to other targets (e.g., Jupiter or a comet)?

b) Is it possible to give an order of precedence to the Mercury scientific objectives in terms of their scientific merit?

c) How much of what we presently wish to know about Mercury can be learned from the ground? How much from an Earth orbiter, a Mercury fly-by, a Mercury orbiter, etc. ?

As these three questions are discussed in turn, it will become evident that in fact they are closely related to each other.

Perhaps the best criterion to use in discussing the relative importance of Mercury as a mission target is the possible contribution which knowledge about the planet might make to the solution of the largest questions which are being asked about the solar system. Three of the most important questions of this type are concerned with the origin of life, the origin and evolution of the solar system, and the influence of extraterrestrial phenomena (e. g., solar flares) on the terrestrial environment. In the first two of these areas we have indicated that a study of Mercury may lead to important results but it is our feeling that other targets are probably more significant. A study of Mercury has very little relevance to the third topic.

Considering the question of the origin of life, it seems clear that the planet Mars should be explored before going to Mercury. Mars is the only planet in the solar system aside from the Earth which appears to have some kind of living matter on its surface. The possibility that some form of life has developed on Mars should certainly be studied before sending a mission to a planet which can only be expected to contain pre-biotic matter.

The problem of precedence becomes more complex when the question to be studied is the manner of the origin of the solar system. As stated in section 8. 7, this problem can only be solved by a study of all or most of the members of the system and their various peculiarities. In this respect Mercury would seem to be as important a target as any other. Yet studies of Jupiter and Venus are probably more germane to this problem and there are two classes of objects in the solar system whose origins are much less well understood than that of Mercury, viz. the comets and the asteroids.

It is customary to divide the planets in two groups. Mercury, Venus, the Earth, Mars, and the asteroids are designated as the terrestrial planets whose common characteristics are relatively high densities, small masses, atmospheres (when present) of secondary origin, and elemental abundances similar to those found in the Earth's crust and in meteorites (as opposed to those in the Sun and stars). The Jovian planets consist of Jupiter, Saturn, Uranus, Neptune, and Pluto (which may be an escaped satellite of Neptune). These planets have large masses, low densities, primary atmospheres, and elemental abundances more similar to those of the Sun and stars. From the standpoint of studies concerned with the origin of the solar system, Jupiter is a very important target since it is representative of a different class of planets from that with which we are relatively familiar from our studies of the Earth itself. In looking for likely targets among the other terrestrial planets (excluding Mars whose importance has already been established), the problems presented by the dense atmosphere, retrograde rotation and high surface temperature of Venus appear

to present a more severe test for any general theory of solar system origin and evolution than the characteristics of Mercury.

Mercury has a high density which is something of a problem but it is relatively easy to put forward a logical explanation in terms of what we know about the Earth and the moon and what we can deduce about the early history of the Sun. The composition of a cometary nucleus and the structure of an asteroid (collision fragment or condensation?) are problems which must be solved before their respective origins can be understood. Moreover, both problems may be extremely relevant to the overall problem of the origin and evolution of the solar system. The asteroids may represent fragments of a larger body which broke up some time after its formation or may be individually condensed out of the primordial solar nebula. In either case a knowledge of their structure and composition will be very useful, either as our only chance to inspect material from the interior of a planet-sized body or as examples of the stuff from which the inner planets were composed. (Clearly the resolution of these two conflicting hypotheses will be an important goal of an asteroid study.) Similarly, the nuclei of comets may also represent debris from planet formation or may be subsequent condensations. Again the opportunity of investigating primordial matter (in the low density as opposed to the high density (asteroidal) form) is presented. In addition, the understanding of the physics of comets may allow their use as probes of the interplanetary medium.

With respect to the third general topic (the influence of extraterrestrial phenomena on the terrestrial environment), a Mercury mission per se would be considerably less enlightening than a mission whose specific purpose was the study of interplanetary fields and particles. Such missions

are contemplated and their scientific objectives have been formulated (Roberts 1964). This represents a good argument for a combined mission which would include instruments for measuring the properties of the interplanetary medium en route to Mercury.

Thus from considerations based solely on scientific merit (i.e., excluding practical considerations such as the availability of necessary instruments and launch vehicles) it is our opinion that a mission to Mercury has a relatively low priority compared to interplanetary studies and missions to Mars, Jupiter, Venus, the comets and the asteroids.

A total evaluation of missions to Mercury must, of course, include the constraints imposed by technology and funding and will be the subject of a separate report. It is clear, however, that a study of the surface and composition of the planet can best be accomplished by means of lander missions. The mass of Mercury and its internal distribution are primary objectives of observations from a Mercury orbiter. A Ranger type of impact mission could yield high resolution surface information and, from throw-out seismometers, information on the state of the planet's interior. A fly-by could provide a better idea of surface relief through pictures of the surface near the terminator.

Magnetic field measurements and improved data on the atmosphere are also fly-by objectives as is a measurement of temperature as a function of position on the disc.

Significant advances in our knowledge of Mercury are possible through new and improved measurements from Earth and Earth orbiting satellites. Microwave observations, spectrophotometry, polarization

measurements and photometry are examples of studies which would be rewarding and which could provide a better base for design of early missions to Mercury.

APPENDIX

Notes to Table 1

Diameter

The diameter of Mercury has been notoriously difficult to measure, values ranging from 5.''7 to 7.''09 (at 1 AU) being quoted in the literature. The best recent determinations were made at the time Mercury passed between the Sun and the Earth in 1960. These have been evaluated and summarized by Dollfus (1963) who derived a weighted mean of $6.''67 \pm 0.05$ at 1 AU which is equivalent to the metric value for the radius given in the table.

Mass

The mass of Mercury has been determined in three different ways with three different results, all of which are discussed in a review by Brouwer and Clemence (1961):

a) Mercury's periodic perturbations on Venus

$$m = \frac{1 \pm 0.077}{5,880,000} M_{\odot}$$ Duncombe

b) Secular perturbations of Mercury and the Earth

$$m = \frac{1 \pm 0.055}{6,480,000} M_{\odot}$$ Brouwer

c) Perturbations of Eros by Mercury

$$m = \frac{1 \pm 0.007}{6,120,000} M_{\odot}$$ Rabe

Brouwer and Clemence point out that the agreement exhibited by the three independent derivations is more trustworthy than the accuracy represented by any one of them. Rabe's value is preferred by these authors; presumably because it has the least internal error and is nearly an average of the other two.

Density

Using his newly determined value for the diameter and Rabe's value for the mass, Dollfus (1964) derived the value for the density which is given in the table.

Period of Rotation

Antoniadi (1934) reports that Schiaparelli's original conclusion (drawn from visual observations made between 1881 and 1889) that Mercury exhibits synchronous rotation was not believed by the majority of astronomers in the early part of this century. Antoniadi's own observations confirmed the 88 day period which has subsequently been generally accepted. A certain amount of skepticism has remained however, (MacDonald 1963), so it is reassuring to find that the radar results corroborate the work of the visual observers (Carpenter and Goldstein 1963).

REFERENCES

Allen, C. W. 1963, Astrophysical Quantities, 2nd ed. (London: Athlone Press).

Antoniadi, E. M. 1934, Smithsonian Institution - Annual Report 1934, p. 99.

Arrhenius, S. 1908, Worlds in the Making (New York: Harper).

Baldwin, R. 1963, The Measure of the Moon (Chicago: University of Chicago Press).

Brouwer, D., and Clemence, G. M. 1961, Planets and Satellites, ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press) p. 31.

Carpenter, R. L., and Goldsteon, R. 1963, Science, 139, 910.

Carpenter, R. L., and Goldstein, R. M. 1963, Science, 142, 381.

Carpenter, R. L. 1964, Astron. J., 69, 2.

Dollfus, A. 1961, Planets and Satellites, ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press) p. 343.

Dollfus, A. 1962, Handbuch der Physik 54, ed. S. Flügge (Berlin: Springer Verlag) p. 180.

Dollfus, A. 1963, Icarus, 2, 219.

Dufay, J. 1957, Galactic Nebulae and Interstellar Matter (New York: Philosophical Library) p. 206.

Field, G. B. 1962, Astron. J., 67, 575.

Fowler, W. A., Greenstein, J. L., and Hoyle, F. 1962, Geophys. Jour. of the Roy. Ast. Soc., 6, 148.

Fox, S. W. 1960, Science, 132, 200.

Gallet, R. 1961, Planets and Satellites, ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press) p. 500.

Gehrels, T. 1963, Appl. Optics, 2, 67.

Hapke, B., and Van Horn, H. 1963, J. Geophys. Res., 68, 4545.

Harris, D. 1961, Planets and Satellites, ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press) p. 272.

Hodge, P. 1963, Proc. Intern. Astrophys. Colloq., 11th, Liege, ed. P. Swings (Liege).

Howard, W. E., Barrett, A. H., and Haddock, F. T. 1962, Ap. J., 136, 995.

Kozyrev, N. 1963, Jour. of British Astron. Assoc., 73, 345.

Kuiper, G. P. 1951, in Astrophysics, ed. Hynek (New York:McGraw-Hill, Inc.) p. 357.

Kuiper, G. P. 1952, The Atmospheres of the Earth and Planets, ed. Kuiper (Chicago: University of Chicago Press), p. 306.

Kuiper, G. P. 1954, Proc. Nat. Acad. Sci. 40, 1096.

Kuiper, G. P. 1957, Ap. J., 125, 287.

Kuiper, G. P. 1963, paper presented at A. A. S. Symposium, Tucson, Arizona, April, 1963.

Kuiper, G. P. 1964, in press.

Lederberg, J., and Cowie, D. B. 1958, Science, 127, 1473.

Lederberg, J. 1960, Science, 132, 393.

MacDonald, G. J. F. 1963, Space Science Reviews, 2, 473.

Miller, S. L. 1953, Science, 117, 528.

Moroz, V. 1964, press release in Pravda, Jan. 15, 1964, p. 4.

Pettit, E. 1961, Planets and Satellites, ed. G. P Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press) p. 400.

Rabe, E. 1957, Ap. J. 125, 290, Ap. J. 126, 240.

Roberts, D. L. 1963, 1964, Scientific Objectives of Deep Space Investigations, ASC/IITRI P-1, P-2, P-3, P-4, P-5.

Sagan, C. 1960, Proc. Nat. Acad. Sci., 46, 393.

Sagan, C., and Kellogg, W. W. 1963, Annual Review of Astronomy and Astrophysics, 1, 235.

Shoemaker, E. 1962, Physics and Astronomy of the Moon, ed. Z. Kopal (London: Academic Press) p. 283.

Urey, H. C. 1951, Geochim. et Cosmochim. Acta., 1, 207.

Urey, H. C., 1957, Physics and Chemistry of the Earth, 2, 46.

Walker, J. C. 1961, Ap. J., 133, 274.

Weinberg, J. L., and Newkirk, G. 1961, J. Planet. Space Sci., 5, 163.

Zabriskie, F. 1962, Astron. J. 67, 168.